Sub sea tunnelling as an option for strait crossings

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Vice President of International Tunnelling and Underground Space Association

Focusing Scandinavian Sub Sea Tunnelling

Scandinavian Sub Sea Tunnelling

Sub sea road tunnels entirely through bedrock - a Norwegian state-of-the-art

- Used for primary and secondary highway connections
- Typically crossing sounds 1 – 4 km wide, bedrock at 30 - 200+ m depth b.s.l.
- Substantially lower cost than bridges and submerged tunnels, even with long tubes and challenging geology
- 22 completed since 1982, 4 under construction
- 1 in Iceland, 2 in Faroe Islands, all: single tube
- Several projects have been looked at in other countries
- A number of sub sea tunnels have been made for oil/gas
Scandinavian Sub Sea Tunnelling

SOME KEY ELEMENTS OF THIS PRESENTATION

- GEOLOGICAL CONDITIONS IN SUB SEA TUNNELS
- COMPLETED NORWEGIAN PROJECTS
  - Road tunnels
  - Tunnels for oil, gas and water
- BASIC PRINCIPLES OF NORWEGIAN TUNNELS
  - Characteristics and main challenges
  - Geo-investigations
  - Excavation
  - Rock support
  - Water control
  - Operational experience
- SUB SEA PROJECTS OUTSIDE OF NORWAY
- FUTURE DEVELOPMENTS

Construction work commenced recently
- Atlanterhavstunnelen, next to Kristiansund
- Finnfast, next to Stavanger
### Scandinavian Sub Sea Tunnelling

**Norwegian sub sea road tunnels - key data of some projects**

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>YEAR</th>
<th>AREA (m²)</th>
<th>GEOLOGY</th>
<th>LENGTH (km)</th>
<th>MIN. ROCK COVER (m)</th>
<th>MAX. DEPTH (m.b.s.l.)</th>
<th>AADT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vardø</td>
<td>1981</td>
<td>53</td>
<td>Shale/sandstone</td>
<td>2.6</td>
<td>28</td>
<td>- 88</td>
<td>670</td>
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<tr>
<td>Ellingsøy</td>
<td>1987</td>
<td>68</td>
<td>Gneiss</td>
<td>3.5</td>
<td>42</td>
<td>-140</td>
<td>2700</td>
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<tr>
<td>Kvalsøy</td>
<td>1988</td>
<td>43</td>
<td>Gneiss</td>
<td>1.6</td>
<td>23</td>
<td>- 56</td>
<td>500</td>
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<td>Godøy</td>
<td>1989</td>
<td>52</td>
<td>Gneiss</td>
<td>3.8</td>
<td>33</td>
<td>-153</td>
<td>725</td>
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<tr>
<td>Nappstraumen</td>
<td>1990</td>
<td>55</td>
<td>Gneiss</td>
<td>1.8</td>
<td>27</td>
<td>- 60</td>
<td>600</td>
</tr>
<tr>
<td>Freifjord</td>
<td>1992</td>
<td>70</td>
<td>Gneiss</td>
<td>5.2</td>
<td>30</td>
<td>-100</td>
<td>1850</td>
</tr>
<tr>
<td>Byfjorden</td>
<td>1992</td>
<td>70</td>
<td>Phyllite</td>
<td>5.8</td>
<td>34</td>
<td>-223</td>
<td>2800</td>
</tr>
<tr>
<td>Hitra</td>
<td>1994</td>
<td>70</td>
<td>Gneiss</td>
<td>5.6</td>
<td>38</td>
<td>-264</td>
<td>635</td>
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<tr>
<td>North Cape</td>
<td>1999</td>
<td>50</td>
<td>Shale/sandstone</td>
<td>6.6</td>
<td>49</td>
<td>-212</td>
<td>300</td>
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<tr>
<td>Oslofjord</td>
<td>2000</td>
<td>78</td>
<td>Gneiss</td>
<td>7.2</td>
<td>32</td>
<td>-130</td>
<td>4000</td>
</tr>
<tr>
<td>Freya</td>
<td>2000</td>
<td>52</td>
<td>Gneiss</td>
<td>5.2</td>
<td>41</td>
<td>-157</td>
<td>530</td>
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<tr>
<td>Bømlafjord</td>
<td>2000</td>
<td>78</td>
<td>Gneiss/schist</td>
<td>7.9</td>
<td>35</td>
<td>-260</td>
<td>2500</td>
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<tr>
<td>Skatestraum</td>
<td>2002</td>
<td>52</td>
<td>Gneiss</td>
<td>1.9</td>
<td>40</td>
<td>- 80</td>
<td></td>
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<tr>
<td>Elksund</td>
<td>2007</td>
<td>71</td>
<td>Gneiss/gabbro/limestone</td>
<td>7.8</td>
<td>50</td>
<td>-267</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL NUMBER: 26**

### Scandinavian Sub Sea Tunnelling

**Norwegian sub sea road tunnels - key data of some projects**

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>YEAR</th>
<th>AREA (m²)</th>
<th>GEOLOGY</th>
<th>LENGTH (km)</th>
<th>MIN. ROCK COVER (m)</th>
<th>DEPTH (m.b.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frierfjord (gas)</td>
<td>1976</td>
<td>16</td>
<td>Gneiss/clayst.</td>
<td>3.6</td>
<td>48</td>
<td>-253</td>
</tr>
<tr>
<td>Karmsund (gas)</td>
<td>1984</td>
<td>27</td>
<td>Gneiss/phylite</td>
<td>4.7</td>
<td>56</td>
<td>-180</td>
</tr>
<tr>
<td>Feredsfjord &quot;</td>
<td>1984</td>
<td>27</td>
<td>Gneiss</td>
<td>3.4</td>
<td>46</td>
<td>-160</td>
</tr>
<tr>
<td>Ferlandsfjord &quot;</td>
<td>1984</td>
<td>27</td>
<td>Gneiss/phylite</td>
<td>3.9</td>
<td>55</td>
<td>-170</td>
</tr>
<tr>
<td>Hjartøy (oil)</td>
<td>1986</td>
<td>26</td>
<td>Gneiss</td>
<td>2.3</td>
<td>38 (6)</td>
<td>-110</td>
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<tr>
<td>Kollsnes (gas)</td>
<td>1994</td>
<td>45-70</td>
<td>Gneiss</td>
<td>3.8</td>
<td>7 (piercing)</td>
<td>-180</td>
</tr>
<tr>
<td>Snøhvit (water)</td>
<td>2005</td>
<td>22</td>
<td>Gneiss</td>
<td>1.1/3.3</td>
<td></td>
<td>-111/54</td>
</tr>
<tr>
<td>Aukra &quot;</td>
<td>2005</td>
<td>20/25</td>
<td>Gneiss</td>
<td>1.4/1.0</td>
<td></td>
<td>- 86/57</td>
</tr>
</tbody>
</table>

**TOTAL NUMBER: 16**
Scandinavian Sub Sea Tunnelling

MAIN CHALLENGES OF TYPICAL FJORD CROSSING TUNNEL

- Project Area Covered By Water
- Often Major Faults / Weakness Zones
- Inclined From Both Sides
- Unlimited Leakage Reservoir
- Saline Leakage Water
- Norwegian geology is a lot more than only good rock quality

DRILL AND BLAST USED FOR ALL PROJECTS, DUE TO:
- GREAT FLEXIBILITY
- COST EFFECTIVENESS

TRADITIONAL UNIT RATE CONTRACT MOST COMMON

"Unlined" Tunnelling!
- Permanent rock support consists of rock bolts and shotcrete/sprayed concrete
- Primary support is approved as permanent if it meets the material standard
- Active design of support to fit the encountered geological conditions
- Water control by grouting
**Scandinavian Sub Sea Tunnelling**

**TUNNEL CLASSIFICATION SYSTEMS**

The tunnel class defines:
- Geometry
- Standard
- Layout/content of technical installations

**NPRA Handbook 021**

**British BD 78/99**

**Scandinavian Sub Sea Tunnelling**

**Some cost figures**

<table>
<thead>
<tr>
<th>Other project</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract award cost Norwegian sub sea tunnels in 2006</td>
<td>In the range of 75.000NOK/km (varying 8000Euro to 12000Euro)</td>
</tr>
<tr>
<td>Complete tunnel cost Nordoyatunnelin (2005)</td>
<td>65.000NOK/km</td>
</tr>
<tr>
<td>Cost estimate for complete tunnel the Skaletpstunnel (2006)</td>
<td>72.000NOK/km +/- 18%</td>
</tr>
<tr>
<td>Estimated costs</td>
<td>Blacmaul Sound</td>
</tr>
<tr>
<td>Tunnel construction, mill. £</td>
<td>14.1 ± 1.2</td>
</tr>
<tr>
<td>Planning and pre-investigation tunnel, mill. £</td>
<td>8.9 – 1.2</td>
</tr>
<tr>
<td>Site supervision tunnel, mill. £</td>
<td>8.9 – 1.5</td>
</tr>
<tr>
<td>Connection roads, mill. £</td>
<td>1.6</td>
</tr>
<tr>
<td>Total project costs, mill. £ (2002)</td>
<td>16.3 – 19.6</td>
</tr>
</tbody>
</table>
Scandinavian Sub Sea Tunnelling

OPERATIONAL EXPERIENCE

- WATER INGRESS REDUCED BY UP TO 50% (SELF SEALING EFFECT)
- ALGAE GROWTH IN SOME TUNNELS
- PERIODICAL REPLACEMENT OF INSTALLATIONS REQUIRED
  - Annual cost for reinvestment/operation & maintenance varies in the range of 400 – 1000NOK/m (2002)
  - 30-50% of this is reinvestment
  - 25-50% represent electricity
- ACCIDENT RATE IN TUNNEL LESS THAN ON OPEN ROADS: 0.1 ACCIDENTS PER MILL. VEHICLE KM PER YEAR VS. 0.25
- A FEW PROJECTS HAVE SPECIAL REGULATIONS ON DANGEROUS GOODS
- 3 CASES OF FIRE, NONE WITH PERSONAL INJURY

Sub sea tunnel projects planned/constructed according to Norwegian concept
### Scandinavian Sub Sea Tunnelling

List of sub sea tunnels outside Norway, planned and/or constructed in accordance with Norwegian concept

<table>
<thead>
<tr>
<th>Location</th>
<th>Completed</th>
<th>Rock type</th>
<th>Cross section m²</th>
<th>Length</th>
<th>Construction time</th>
<th>Cross section and alignment</th>
<th>Cross section and alignment</th>
<th>Construction time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reykjavik</td>
<td>1998</td>
<td>Basalt</td>
<td>55/65</td>
<td>5.8km</td>
<td>Appr. 21/4 years</td>
<td>4,8km, 6,1km</td>
<td>2 projects 2,6km &amp; 4,6km</td>
<td>Estimated 3 years</td>
</tr>
<tr>
<td>Barentsburg</td>
<td>2002/2006</td>
<td>Basalt</td>
<td>85</td>
<td>4,9km</td>
<td>Appr. 21/4 years</td>
<td>Various alignments 4,3-6,1km</td>
<td>2 projects 2,6km &amp; 4,6km</td>
<td>Estimated 3 years</td>
</tr>
<tr>
<td>Skaraberg</td>
<td>2006</td>
<td>Basalt, Granite</td>
<td>55/65</td>
<td>5,1km</td>
<td>Pre-feasibility</td>
<td>3 projects 3 to 13km</td>
<td>5-10 km</td>
<td>Not decided</td>
</tr>
<tr>
<td>Åland</td>
<td>Initial</td>
<td>Granite</td>
<td>75</td>
<td>5.5 km</td>
<td>Pre-feasibility</td>
<td>3 projects 3 to 13km</td>
<td>5-10 km</td>
<td>Not decided</td>
</tr>
<tr>
<td>Orkney Islands</td>
<td>Initial</td>
<td>Granite, granite, gneiss</td>
<td>75</td>
<td>5.5 km</td>
<td>Pre-feasibility</td>
<td>3 projects 3 to 13km</td>
<td>5-10 km</td>
<td>Not decided</td>
</tr>
<tr>
<td>Schleswig</td>
<td>Initial</td>
<td>Granite</td>
<td>75</td>
<td>5.5 km</td>
<td>Pre-feasibility</td>
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<td>5-10 km</td>
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</tr>
</tbody>
</table>

**Note:** Estimated dates and distances may vary.
Scandinavian Sub Sea Tunnelling

- The Hvalfjordur tunnel was planned and built by Spölur hf, a private enterprise that was granted concession to undertake the project.
- It was financed by external founding (loan from), no public financing.
- Spölur is operating the project, concession allows toll payment, ferry was taken out of service.
- Concession includes 20 years of operation, IPRA to take over project free of charge.

Scandinavian Sub Sea Tunnelling

The Hvalfjordur tunnel, longitudinal section

- Length: 5570 m + 280 m portal
- Max. inclination: 8%
- Lowest point: -135 mbsl
- Minimum rock cover: 38m
- Maximum water depth: appr. 40m
- Sediment thickness: appr. 80m
- AADT: Design traffic of 2500 vehicles
- Cross-section width: 8,5m and 10m in one, single tube
Scandinavian Sub Sea Tunnelling

Geological conditions Hvalfjordur tunnel
- Iceland is cut into 2 by the North – Atlantic active rift at only some hundred km’s distance to the project site
- Project site is located some 10-40km west of the so-called Reykjanes volcanic zone
- The bedrock is only 3 mill years old
- The bedrock is mainly composed of layers of basalt gently sloping towards southeast
- The tunnel face was dominated by mixed-face
- The area is prone to active seismicity/tectonic events

Scandinavian Sub Sea Tunnelling
- The public believed the project was "an engineering fiasco"
- A careful design was conducted including:
  - Risk analysis performed by the Owner prior to construction
  - Contractors system analysis focusing: geological hazards, heat problems, harmful gases, seismic damage, water inflow and tunnel durability
- Contracted according to BOT:
  - Adjustable fixed price construction contract
  - Contractor performed all detail design
  - Comprehensive "as built" documentation
- Systematic probing/pre-grouting ahead of tunnel, a key to success
Scandinavian Sub Sea Tunnelling

Experiences from construction and operation
- Tunnel construction took 21/4 years, i.e. 6 months shorter than scheduled, average excavation progress of 90m/week (45m per tunnel excavation face)
- Hot water encountered reached a max. of 57 degrees C
- Support by appr. 3.25 rock bolts per m and 60-80mm thick sprayed concrete (no shotcrete lining applied)
- Continuous probing ahead of face and pre-grouting according to pre-set criteria (inleak today is 55 l/min/km compared to max. allowable level of 300l/min/km)
- Extreme traffic growth from an optimistic 1800 AADT to about 5000 AADT as per 2006
- Earthquake of almost 6 did not cause any damage to the tunnel or its installations

Red line is the existing tube
Dotted line is a schematic location of a future second tube

Future challenges:
- To meet the steadily increased traffic
- Maintain a high service level
- Continue “uninterrupted” operation during the construction of a second tube
- Upgrade the first tube to match the standard level of the new one
Scandinavian Sub Sea Tunnelling

Sub sea tunnelling projects in the Faeroe Islands

- An infrastructure revolution
- Network of sub sea tunnels, some constructed and some planned, ties these islands together
- 2 in operation at present
- 2 more at planning stage
- All sub sea tunnels in the Faeroe Islands have been designed and built according to Norwegian codes
Scandinavian Sub Sea Tunnelling

- The Faeroes population is about 50,000 people
- An annual average daily traffic of about 500 at the current ferry connections
- Design basis is AADT 1,000 and 2,000 for the 10th and 20th operation year respectively
- Typical low traffic volume tunnel
- Norwegian tunnel codes and guidelines were found applicable and constitute the design basis
- These include standards for low traffic tunnels enabling such projects to be cost-beneficial
- The projects were organized by forming private enterprises that were partly public and privately financed, granted concession to build and operate these projects
- Concessions include the responsibility to plan, design, construct and operate the tunnels based on toll revenues

The geological conditions include 50 mill years old basalt, laying stable in horizontal layers
- Tectonically stable region
- Cut by dykes, laminated zones, but no real tectonic fault zones were identified
- Uncertainty was specifically related to water inflow
Scandinavian Sub Sea Tunnelling

Vagatunnelin, tunnelling across the Vestmannsund

Some key figures
- Length: 4.9 km
- Min. rock cover: 30m
- Max. Depth: 105mbsl
- Max. Water depth: 60m
- Max. Inclination: 7%
- Cross section width: 10m
- No. of tubes: 1 single tube

Scandinavian Sub Sea Tunnelling

Experiences gained from the Vágatunnelin

- Tunnelling concept was fully applicable
- The rock support and rock mass grouting was more or less in line with the expectations and did not differ from Norwegian experiences
- The pre-investigations performed did not yield any particular difficult weakness nor were any surprises found during tunnelling
- The traffic has seen a steady growth after tunnelling opening

Opening of the Vágatunnelin took place a little more than 2 years after the construction work commenced
Scandinavian Sub Sea Tunnelling

An example of project development, the Nordoyatunnelin in the Faeroe Islands

Some Key data
- Length: 6.2 km
- Water depth max: 105m
- Cross section: 10m
- Max. Inclination: 6%
- Max. rock cover: appr. 650m
- Min. rock cover: appr. 35m

Planning and investigation started in 2001, Construction started January 2004, Break through excavation work mid 2005, Grand Opening to the public was July 2006
Typical investigation methods for sub sea tunnels:

- Review of existing data, desk study
- Surface geological mapping
- Acoustic survey done in initial stage 12 km²
- Side scan sonar
- Several surveys for refraction seismics, totally 8400 m
- Core drilling, 3 vertical holes
- Particular focus on portal areas, low rock cover, geological structures potentially adverse rock
Scandinavian Sub Sea Tunnelling

Shetland Islands

- Sub sea tunnels have been evaluated in a pre-feasibility study to replace current ferry connections in inter islands connections (report in 2002)
- No similar projects exist in these islands and at the time of conducting the study it was all new technology, and new barriers to brake for the public
- Norwegian concept used in pre-feasibility study as this was found well documented

Scandinavian Sub Sea Tunnelling

Bluemull Sound (Yell to Unst)

Some key data

- Length 2,6 km sub sea tunnel
- Max water depth 40m
- 8% inclination
- Min. rock cover 40-45m
- Single tube, bi-directional traffic
- Cross-section appr. 70m2
- Estimated construction time: 19-30 months
- Metamorphic rock: gneiss, schist
Scandinavian Sub Sea Tunnelling
Yell Sound (Yell to Mainland)

Some key data
- Length 4.6km
- Single lane
- Bi-directional traffic
- Cross section 70m²
- Min. rock cover 38m
- Inclinations of 6% & 8%
- Estimated construction time: 31-42 months
- Metamorphic rock as gneiss and schist

Scandinavian Sub Sea Tunnelling

FUTURE DEVELOPMENTS
- MANY MORE SUB SEA TUNNELS IN NORWAY, INCLUDING
- SUBSEA TUNNELS WITH Y-JUNCTION AND ROUNDABOUT
- LONGER AND DEEPER:
  - Rogfast: 24 km / 400 m.b.s.l.
  - Hareid-Sula: 17 km / 630 m.b.s.l.
- SIMILAR PROJECTS IN OTHER REGIONS:
  - Shetland Islands
  - Orkneys
  - Greenland
  - Åland
- ADAPTATION TO EU TUNNEL SAFETY DIRECTIVES
  - TERN-tunnels: Max. gradient 5%
  - TERN-tunnels with AADT>4000: special requirements concerning safety
  - Handbook 021 on Road Tunnels
Scandinavian Sub Sea Tunnelling

CONCLUSIONS SUB SEA TUNNELLING CONCEPT

- It is proven technology, tested and developed during more than 25 years of implementation and operation
- The concept is well documented, precaution is in focus, working procedures, experienced personnel and true commitment are important factors to secure success
- The concept has also been implemented and tested in foreign circumstances compared to Norwegian geological and contractual environment